NASA Contractor Report CR-159015

# Microwave Remote Sensing Laboratory Design

E. Friedman

The MITRE Corporation



Contract No.: F19628-78-C-0001
March 1979

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Abstract

The application of active microwave remote sensing to the study of the ocean surface has a long history, much of it related to determination of sea state. The hardware and software tools developed for that purpose have been effectively adapted to the remote sensing of the polluted ocean, particularly the case when the surface is covered with oil. Instrumentation making use of passive microwave sensing has also been developed specifically for the purpose of studying the polluted ocean.

This report surveys these previous research efforts, both in the field and in the laboratory, to derive guidance for the design of a laboratory program of research by NASA, Langley Research Center. The essential issues include: choice of radar or radiometry as the observational technique; choice of laboratory or field as the research site; choice of operating frequency; tank size and material; techniques for wave generation and appropriate wavelength spectrum; methods for controlling and disposing of pollutants used in the research; and pollutants other than oil which could or should be studied.

TABLE OF CONTENTS

TABLE OF CONTENTS (Concluded)

LIST OF ILLUSTRATIONS

## LIST OF TABLES

SUMMARY

Release of pollutants into bodies of water is a clear threat to the environment. Pollutant impacts include the massive and immediate damage caused by oil tanker collisions and sinkings as well as the less obvious but equally troublesome release of toxic materials into the water from thousands of sewage treatment plants, industrial complexes and other sources. Detection and control of these materials could be more effective if remote sensing techniques could be developed, particularly for airborne use. To be effective, the sensors would have to be capable of detecting, identifying and quantifying the pollutants. Promising results have been achieved by using various parts of the electromagnetic spectrum, including visible, infrared and microwave. The microwave techniques, which are discussed in considerable detail in this report, have achieved a level of sophistication which has resulted in their application as an operational tool in the Coast Guard effort to detect the presence and amount of spilled oil.

The continued improvement of microwave systems will require laboratory studies of the various sensing methods as well as the wide variety of pollutants which might be detected. It is the purpose of this study to identify the essential elements of laboratory experiments and determine the feasability of various alternatives.

This study reviews the current state-of-the-art in the two microwave sensing methods; active (radar) and passive (radiometry). In addition to describing the physical mechanisms which are or might

be exploited to detect the various pollutants, the report discusses the experiments which have made use of microwave remote sensing. These experiments include applications of both active and passive methods, in the laboratory as well as in the field. Virtually every experiment to date has involved the attempted detection of oil, both because of the effectiveness of both active and passive microwave sensing of surface-borne pollutants and because of the pressing need for improved detection and quantification of oil spills.

The potential application of microwave methods for other than oil pollutants is also described in the report.

The results of the study can be summarized as falling into the following categories:

- Capabilities and limitations of radar
- Capabilities and limitations of radiometry
- Important design criteria for experiments
- Pollutants (other than oils) for which microwave remote sensing might be applied.

The remainder of this summary presents the key points relating to each of these topics.

Radar - This method provides a capability for all-weather, day-night observation of oil spills and a limited number of other pollutants. Radar produces an image of the polluted region by detecting the suppression of small waves by the oil slick. The usual platform for deployment of the sensor is an aircraft, so that fairly large areas

can be covered in a short time. While the technique does not appear capable of providing information on oil type or film thickness, it is an effective method for determining the location and areal extent of the pollution. The sensing method relies on the suppression of the short wavelength water waves to which the radar is sensitive. It is therefore necessary to have some surface roughness in the vicinity of the spill so that the contrast between clean and polluted water is high. In very rough seas, the method is limited by the break-up of the oil slick.

Radiometry - As in the case of radar, radiometry provides all-weather, day-night observational capability. This method relies upon detection of the thermally emitted radiation produced by the oil layer and the water under it. Because the oil is a more effective radiator than water, it appears warmer than the clean water areas. The contrast in apparent temperature provides the means of detection. After correcting the radiation for the reflected skylight and sunlight which reaches the detector, the information can be used to map the extent and thickness of the slick. Estimation of slick thickness requires information on the physical characteristics of the oil, including its temperature and emissivity. Interference effects within the oil layer, and which are a function of the thickness of the layer, reveal the film thickness up to a limit determined by

experimental conditions. Use of two observation frequencies provides a means for further extending the range of thicknesses which can be detected.

The foregoing description of the performance of radiometers applies to observations made in the laboratory when the oil is dispersed on a smooth water surface. Conditions are somewhat different in at-sea tests. The waves on the ocean surface contribute a roughness effect, which results in a radiative signal which is higher than that of a smooth ocean surface. The effect of the oil is to suppress this added signal by damping the short wavelength part of the roughness, which contributes most of the signal. At the same time, the oil contributes a signal of its own. The result of these competing effects sometimes results in a signal larger than that contributed by the surrounding ocean, sometimes lower. The confusion associated with the two effects can limit the usefulness of radiometry for studies at sea.

The ability of oil to suppress waves and produce a signal smaller than that of the surrounding clean water, provides a sensitivity better than that found in the laboratory, where the method of detection is the higher signal associated with the emission of radiation from the oil. The increased sensitivity associated with wave suppression is particularly evident for very thin films, which contribute little to the radiant signal, but are almost as effective as thick oil slicks in suppressing waves.

Experiment Design - The review of recent research in microwave remote sensing of aquatic pollution has resulted in a number of conclusions regarding the possible design of a laboratory facility. The results can be conveniently organized in three categories:

Concept

Transmitting and Receiving Equipment, and

Tank Design

Concept - The laboratory facility would involve the organization of the following equipment and materials into a functioning research entity; receiver, transmitter (in the case of radar), tank, materials to be tested, mechanisms for agitating the water surface, methods for measuring the concentration (or, in the case of oil, thickness) of pollution, and equipment for clean-up of the tank. The only fundamental limitation associated with assembling such a laboratory is the inability to perform radiometry experiments in a building or other enclosed volume (due to radiation, emitted by the walls and ceiling, which reaches the receiver). Before embarking on a program to develop such a facility, consideration will have to be given to making use of existing water tank facilities, many of which have been used for microwave studies. Location of an adequate facility will clearly simplify the process of initiating a research program. It will also minimize the costs required to establish the necessary physical plant. Indoor research tanks could be utilized in the event that the program is to address radar applications.

An alternative to tank experiments is the use of accidental, natural or planned oil spills. A number of researchers have chosen this method alone, or in conjunction with laboratory studies. Problems with this method include an inability to predict the location or time of occurrence of appropriate test sites, limited ability to control experimental conditions and only limited information on the type of pollution and surface conditions. In addition, the use of slicks left by sludge barges, which offer a source of oil which is predictable in time and location, does not offer an identification of the constituents of the slick. Further, the foam produced by the ships has an emissivity higher than that of the surrounding ocean, making data interpretation more difficult.

Transmitting and Receiving Equipment - The survey of laboratory and field experiments carried out in this report has resulted in the definition of typical experimental conditions. The frequency chosen, either for radiometry or radar, will be in the vicinity of 37 or 94

Ghz. These frequencies fall in two of the more transparent regions of the atmosphere within the microwave spectrum. For complete flexibility in experiment implementation, the receiver should be capable of operating in either horizontal or vertical polarizations. For radar, a capability for dual polarization transmitting is also recommended.

Normally, the receiver is oriented to view the surface at an angle of approximately 45°. For complete flexibility, however, a variable viewing angle is recommended. The detector assembly should be of sufficiently high sensitivity and low noise to allow operation under a wide variety of conditions.

Detector systems in the microwave frequency range have relatively large fields-of-view, compared to the optical case. For this reason, care must be exercised to confine the field-of-view of the receiver (and transmitter, if appropriate) to within the confines of the tank or oil spill area.

Tank Design - The design of a tank system for experiment applications will require a container of sufficient size to intercept the transmitter/receiver beam as well as allow the oil to spread to a mono-layer, if desired. Tank depth is not an important factor since the penetration of microwaves into water is very limited. Tanks of a wide variety of sizes and depths have been used in experiments carried out to date. In addition, virtually any material can be used for fabricating the tank. Precautions must be taken, however, to limit emissions or reflectance from surrounding equipment which might reach the detector. This should not be a problem, however, for a tank of the proper size relative to the antenna beam width.

A properly designed tank facility will include the ability to generate waves. For the most effective simulation of the conditions found at sea, both mechanical wave-makers and wind generators should be used. The wind generator is capable of generating the short wavelength waves which provide the contrast needed to detect the presence of oil.

In order to confirm the performance of remote sensors used in the tank facility, equipment should be available for the measurement of the oil film thickness and volume. This is particularly important in the case of passive systems, since they have the capability to make these measurements and require calibration. The most common method for making these calibration measurements has been to measure the volume of oil used in the experiment and measure the area of the film. Improved methods are required, however, because of the non-uniform films which can result from experiments on heavy oils or with heavy wave action.

Water treatment and material handling capabilities are additional requirements of a tank facility. Water treatment involves the ability to make available sufficient quantities of clean water, with controlled concentrations of salts adequate to simulate conditions ranging from fresh to ocean water. Material handling includes the safe storage, use and disposal of the various pollutants which might be used in the tank. Pollutant dispensing methods should be capable of creating a uniform oil film, if desired, as well as incremental increases in film thickness. The ability to effectively clean the tank of the pollutants is another requirement. The cleaning system must be capable of removing any type of pollutant used in tests.

Pollutants - To be most effective, the research program should be designed to have sufficient flexibility to allow study of oil (the most commonly researched pollutant, to date) as well as a wide variety of other pollutants. The capabilities of the remote sensing systems under study can be classified as relating to their ability to detect, identify and quantify the pollution. The study itself provides specific details on the chemicals which are susceptible to detection and quantification. Identification of specific pollutants, either by active or passive methods, is not possible. The highly unique absorption spectra needed to make identification possible do not exist in the microwave region for fluid pollutants.

The pollutants which can be detected and quantified are primarily those which are hydrophobic and lighter than water. These properties concentrate the pollutant on the water surface where it is relatively easy to detect. A smaller group of pollutants is detectable as a result of their solubility in water and their impact on the water's conductivity. This type of effect is only useful in a fresh water environment, since the salts dissolved in the ocean mask the presence of the pollution.

Finally, the performance of the two sensor methods can be generally described as follows:

passive: 1,000 ppm concentration of pollution in fresh water
1-100 micron thickness of oil film, and

active : film thickness greater than 1 micron

In the final analysis, financial issues will have a considerable influence on any plans to develop a laboratory capability. The cost for a complete facility for both radar and radiometry experiments on oil and other pollutants is likely to be very high relative to the alternatives. They include existing indoor and outdoor tank facilities (with or without microwave equipment) and at-sea tests using natural, accidental or deliberate pollution spills.

## 1.0 INTRODUCTION

The environmental impact of spills of hazardous pollutants (particularly oil) is well established as a threat to the ocean. The severity of the problem requires improved methods of locating the spill, quantification of the size of the spill, identification of the type of pollutant and its concentration, determination of the efficiency of clean-up operations and a capability for patrolling for accidental or intentional spills.

A wide variety of electromagnetic detection methods have been presented as techniques with these capabilities.(1) Ideally, a remote sensor system should be capable of detecting the presence, location, extent, volume and type of pollutant under a wide range of oceanic and atmospheric conditions either during the day or at night. It is in the context of all-weather, day/night observational capability that microwave remote sensing has been explored. A large number of publications have dealt with the capabilities and limitations of both passive and active (radar) microwave systems to detect oil on water (see Bibliography). Additionally, work has been carried out to determine their ability to detect, quantify and identify other important pollutants.(2)

The purpose of this document is to summarize the current state-of-the-art in applying microwave techniques to remote sensing of aquatic pollution. In so doing, reviews are included of experiments, both in the laboratory and the field, as a basis upon which to develop recommendations. The recommendations deal with the

development of a microwave remote sensing laboratory concept which would complement the already existing NASA/Langley capability for studies of polluted water with visible and near-infrared instruments. This capability includes a large water tank facility capable of supplying very clean water, which is then polluted with controlled amounts of various pollutants and sediments. The facility is equipped to measure the spectrally-dependent upwelling radiation produced by a solar simulator. In addition, associated instruments allow the determination of the optical properties of the water, both in its clear and polluted states.

Microwave remote sensing methods can be divided into active (radar) and passive (radiometric) systems. Radar relies on the transmission of a microwave signal and subsequent detection of that part of the energy reflected back to the receiver. Radiometers rely on the naturally-emitted radiation associated with the black-body spectrum of the target. In each case, the radiation propagates effectively through thin clouds, light rain and other atmospheric effects which would normally preclude remote detection. Table 1-I briefly describes some important features of both sensor types. More specific details and additional information are presented in the remainder of the report.

Table 1-II illustrates the performance which can be expected when applying these sensing techniques to the detection of oil on water. It is clear that radiometric methods are generally superior to radar in each measurement category. This result is reflected in

TABLE 1-I

CHARACTERISTICS OF MICROWAVE REMOTE SENSING SYSTEMS (After 1)

| | Radiometry | Radar |
|---|---|---|
| Sensor System | Scanners and Single View Angle | Scanners and Scatterometers |
| Frequency Interval | 30 to 300 gigahertz (Ghz) | 0.23 to 36.1 Ghz[5] |
| Spatial Resolution | 10 milliradians | 10 milliradians |
| Atmospheric Penetration[1] | Haze, smoke, fog | Haze, smoke, fog, rain[2] |
| Day/Night Capability | Yes | Yes |
| Real-Time[3] | Yes | Potentially Exists |
| Geometric Rectification[4] | Poor/Fair | Fair |

1 - Denotes conditions which can be penetrated.
2 - Penetration increases with decreasing frequency.
3 - Immediate presentation of data products.
4 - Potential for planimetric mapping.
5 - Other definitions of radar band ranges from 0.3 to 40Ghz.

TABLE 1-II

APPLICABILITY[1] OF VARIOUS SENSOR SYSTEMS FOR THE MONITORING OF OIL SLICKS ON THE OPEN OCEAN (after 1)

| Sensors | Frequency(Ghz) | Detection | | Areal mapping | | Measurement[3] | |
|---|---|---|---|---|---|---|---|
| Passive microwave | | | | | | | |
| Radiometer | 10-300 | E/G | | F/P | | G | |
| Scanning Radiometer | 10-300 | E/G | | F/P | | F/P | |
| Radar[2] | | | | | | | |
| Polarization[4] | | HH | VV | HH | VV | HH | VV |
| P band | 0.236-0.390 | P | F | P | F | P | F |
| L band | 0.90-1.579 | P | F | P | F | P | F |
| C band | 3.1-6.3 | P | F | P | F | P | F |
| X band | 5.2-11.1 | P | P | P | P | P | P |

1 - Estimates of applicability reflect the opinions of the authors of reference 1 based on their own research and a survey of the literature available to date; the relative value of each system is indicated where: E = excellent, G = good, F = fair, P = poor.
2 - While radars operate within the microwave region, their utility is significantly different from that of microwave radiometers.
3 - Measurement refers to the potential of a system to collect information on the type and thickness of an oil slick.
4 - First letter refers to polarization of transmitted signal (H - Horizontal, V - Vertical) and Second letter refers to polarization detected by receiving antenna.

the number of researchers emphasizing radiometric techniques as noted in the Bibliography.

Table 1-III illustrates the performance requirements developed for radar remote sensing of water pollution. In developing the chart, the authors (3) refer to a variety of oceanic pollutants and effects which occur on the surface.

Section 2 of this report describes the mechanisms by which radar can be applied to remote detection. Because of the emphasis in recent experiments on the application of radar to the detection of oil on the ocean, that topic is emphasized in Section 2. The use of radar for the detection of other pollutants is covered in Section 5.

Section 3 provides a similar description of the techniques used in the application of passive sensing systems. Section 4 summarizes the results of a survey of recent experiments, both in the field and the laboratory. The results of the survey are presented as a group of guidelines to be applied in the development of new research efforts. The topics considered include: the selection of the wavelength of operation, design and fabrication of the tank and performance of sensor systems.

Section 5 is a discussion of the general and specific types of pollutants, other than oil, which might be detected, identified or quantified with microwave remote sensing. Section 6 summarizes the current state of experimentation and application of microwave techniques in detecting aquatic pollution. Section 7 summarizes the conclusions of the study.

TABLE 1-III

ESTIMATED RADAR FUNCTIONAL REQUIREMENTS FOR MONITORING WATER POLLUTION (AFTER 3)

| OBJECTIVE | FREQUENCY RADAR BAND[a] | SPATIAL RESOLUTION, m | GRAY RESOLUTION | TEMPORAL ASPECTS | POLARIZATION | LOOK DIRECTION | ANGLE, DEG | COMPLEMENTARY REMOTE SENSORS REQUIRED | PLATFORM |
|---|---|---|---|---|---|---|---|---|---|
| Oil slick detection and monitoring. | X | 10 to 30 | Conventional | Spill report and monthly in hazard areas. | Vertical | Side | 20 | No, but desirable | Aircraft |
| Debris spill detection and monitoring. | P,X,L,C | 0.5 | Fine under some conditions | Spill report and monthly in problem areas. | Vertical and horizontal. | Side and down. | Unknown | Yes | Aircraft |
| Surface effects of effluent discharge detection and monitoring. | P,X,L,C | 0.5 | Fine under some conditions | Intervals specified by control agencies. | Vertical and horizontal. | Side and down. | Unknown | Yes | Aircraft |
| Monitoring pollution effects, algal mats, and so forth. | P,X,L,C | 1 to 10 | Fine under some conditions | Seasonal or semiannually. | Vertical and horizontal. | Side and down. | Unknown | Yes | Aircraft and possibly spacecraft |

[a]Synthetic aperture

## 2.0 RADAR

### 2.1 General Discussion

The application of radar to remote sensing of the ocean surface has been widely reported, particularly as a tool for determination of the wave height spectrum. This is accomplished by making use of so-called "side-looking" radar. The instrument views the surface by scanning in a vertical plane perpendicular to the flight path. Typically, identical transmitter/receiver systems operate on the two sides of the aircraft. The return signal is proportional to the fraction of the ocean surface agitated by waves such that a reflecting surface is oriented toward the sensor. In fact, the return signal is primarily due to waves having the characteristic that(2)

$$L = \frac{\lambda}{2} \operatorname{Sec} \theta \qquad (1)$$

where $L$ = water wavelength

$\lambda$ = radar wavelength

$\theta$ = depression angle of beam, measured downward from horizontal

For example, a four-frequency radar developed by the Naval Research Laboratory(4) operates from 0.428 to 8.91 Ghz and is sensitive to water waves in the range from 1.5 to 35 cm in wavelength.(5)

The ability to detect these waves has evolved into a method for remote detection of oil. The presence of oil on the surface suppresses the shorter wavelength waves and results in a smaller signal

over the oil-covered area. The ability of oil to suppress waves is reported in terms of the mean square slope reduction. The presence of oil can reduce the mean square slope of the surface (relative to unpolluted regions) by a factor of two or three.[6] Theoretical calculations also indicate that 30 cm waves are reduced by a factor of 10 and shorter wavelength waves are essentially eliminated. Other workers[7] indicated that water wavelengths between 1 and 500 centimeters can be strongly affected by oil films, depending on the thickness.

The contrast produced by wave suppression allows imaging of the polluted area even for film thicknesses which are quite small. Films in the micron range can exert sufficient influence on water waves that the polluted area becomes detectable by remote sensing.[5,7,8,9]

The quality of the observations is a function of the oil thickness, sea surface conditions, microwave frequency and polarization. For example, a completely calm surface precludes making any measurements since there will be no background signal from waves (and hence, no contrast). At low sea state (and low wind), the presence of a micron (or thinner) layer of oil is sufficient to produce a signal.[8] In fact, each of the four frequencies of the NRL radar (0.428, 1.228, 4.455 and 8.910 Ghz) was able to detect thin films ($\approx$1 micron) in an at-sea test.[8] For frequencies above about 1 Ghz, the images were sharper than for lower frequencies. Vertical polarization signals produced higher contrast than horizontal

polarization signals as predicted by theory.[10] In another study of the NRL radar[5], it is reported that thin films (1 micron) are best detected by lower frequencies (1-3 Ghz) in low sea states while higher frequencies (>5 Ghz) may be better at higher sea states. The limitations in this type of remote monitoring are also clear. As the seas become heavy, the thinner films will tend to break up, so that patches of open ocean will appear and the radar observations will become less reliable. In addition, the method is not capable of measuring oil type or thickness[2,5] (although laboratory experiments[11] have demonstrated a limited capacity to do so). Furthermore there is little hope to apply radar observations to soluble substances[2] due to poor propagation of the radiation through water. Finally, because of the way in which data are recorded on film, display of a record of the data is delayed for several minutes by the required film processing.[5] This, too, represents a limitation to the usefulness of this technique.

Radar remote sensing requires a surface covered nearly uniformly by short wavelength waves so that the contrast is high. Finally, spatial resolution of this method is poorer than with other, shorter wavelength, remote sensing methods (such as photography, television, or infrared imagery).

Airborne radar remote sensors have the capability to:

- cover large areas in small time (making use of both aircraft velocity and cross-track scanning)
- operate under most adverse weather conditions

- rely on fairly well developed models of the interaction of microwave radiation with the surface of the ocean

- make use of the highly sophisticated hardware which is readily available

- produce maps (or images) of the polluted region on both sides of the aircraft track

- measure film thickness as small as microns.[11]

## 2.2 Sensing Methods

The general radar remote sensing technique described in Section 2.1 has two forms which are commonly employed; real aperture side-looking radar and synthetic aperture side-looking radar. The real aperture system scans in a plane perpendicular to the flight path. The scan line begins near the aircraft (about 2.5 km away from an altitude of 3 km[10]), and may reach a range of 160 to 250 km from high altitude.[5] The return signal is used to modulate a light source which exposes a film strip which is produced at a rate proportional to the aircraft velocity. The range of scan of the radar antenna can be modified so that, for example, a strip of ocean at a distance can be surveyed or an area close to the aircraft can be studied. The area directly under the aircraft (and out to a range where the normal scan begins) must be studied by some other technique. The resolution of real aperture side-looking radar (and any other antenna system) is limited (assuming ideal conditions) by diffraction. The angular resolution can be expressed as

$$2.44 \frac{\lambda}{D}$$

where $\lambda$ is the microwave wavelength and D is the antenna aperture.

The resolution at the target is then,

$$2.44 \frac{\lambda}{D} R$$

where R is the length of the path from sensor to target. In synthetic aperture radars, the resolution along the flight path is improved by increasing the rate of observations so that the sensor movement between observations is smaller than the instantaneous field-of-view of the receiver. Subsequent analysis of the data allows resolution improvement over that obtained from real apertures. The theoretical resolution limit can be shown to be approximately (D/2).[12] Note that the theoretical limit is independent of operating wavelength and range and is linearly proportional to antenna size, so that very high resolutions might be expected.

The drawbacks of this technique are, however, not trivial:

- the accuracy of the measurements must be high
- data storage and processor requirements increase as the data rate increases
- the radiated power must increase sharply as D is decreased
- a trade-off exists between improved resolution and signal-to-noise ratio at long distances.

The same principle of resolution improvement through over-sampling can be applied to improve resolution in the plane of the scan by, again, over-sampling, storing and processing the information.

The production of images of oil-polluted regions by radar is, in summary, a relatively straight-forward technique, based on technical

advances developed for other applications. Another, slightly different tool, involves the detection of radar signals on a calibrated basis, so that quantitative analysis of target features can be performed. Such a method is called scatterometry. Scatterometers provide information on the effective cross-section of interaction as seen by the radar system.[12]

## 3.0 PASSIVE MICROWAVE RADIOMETRY

All materials emit thermal radiation as a function of their temperature and emissivity. The considerable difference between the emissivities of oil and water is used to both detect the presence of oil slicks and quantify their volume by estimating the area covered and the thickness of the slick. As noted in Section 5, other pollutants which float on the surface of water may also be detected by this mechanism. Dissolved chemicals may affect the emissivity of the water and thus be detected, but this is only likely in fresh water since the conductivity of the ocean resulting from dissolved salts masks the effect of the pollution.

### 3.1 Properties of Plane Layers of Dielectric Media

In an ideal case, a uniform layer of oil is distributed over a completely flat water body and is viewed from above by a microwave radiometer. In addition to the radiation upwelling from the oil-water system, radiation emitted by the sky is reflected by the surface and reaches the radiometer. The problem is essentially identical to the standard electromagnetic analysis involving layered dielectric media.[13]

First, let us give consideration only to that part of the detected signal associated with emissions from the oil-water combination (the effect of skylight reflections will be dealt with subsequently). The apparent temperature of the water surface is the product of the actual temperature of the oil-water combination ($T_w$) and the effective emissivity (e).

The emissivity is a complex function[14] of viewing angle, reflection coefficients between the air-oil and oil-water interfaces (themselves functions of the various dielectric constants, which are complex) and polarization. Because of interference effects within the oil film, the effective emissivity oscillates as a function of film thickness. This effect has been observed in laboratory studies[15] and confirms the theoretical prediction that the apparent temperature of the fluid is equal to the real temperature for film thicknesses of 0, $\frac{\lambda}{2}$, $\lambda$, ... (where $\lambda$ is the wavelength in oil). For film thicknesses of $\frac{\lambda}{4}$, $\frac{3\lambda}{4}$, $\frac{5\lambda}{4}$, ... the emissivity is maximized and the apparent temperature of the scene is increased by an amount $\Delta T$, over that of the surrounding water. At the same time, the reflection coefficient of the oil-covered water varies with film thickness in the opposite way (is maximized when emissivity is minimum, etc.).[14,15]

Thus, the signal associated with increased emissivity is

$$\Delta T = eT_w - e'T_w \qquad (2)$$

where e' is the emissivity of the water surrounding the slick.

It is now appropriate to include the effect of reflected sky radiation, $RT_{sky}$, where R is the reflection coefficient of the oily surface and $T_{sky}$ is the effective sky temperature. The antenna then sees an increased temperature relative to clean water of

$$\Delta T_a = eT_w - e'T_w + RT_{sky} - R'T_{sky} \qquad (3)$$

where R' is the reflectivity of the unpolluted water.

### 3.1.1 Data Analysis

The increase in apparent temperature of the scene in which an oil spill is present must be corrected for the radiation reflected from the sea surface. Troy and Hollinger[16] describe their procedure for this process, as summarized below.

The signals derived from the antenna are organized into the two-dimensional array which represents a grid from which an image of the slick will be formed. This includes taking into account the viewing angle, aircraft velocity and altitude for each of the data points. The effect of upwelling sky reflections is removed from each data point through[16]

$$\Delta T_b = \Delta T_a \left( \frac{1}{1 - \frac{T_{sky}}{T_w}} \right) \tag{4}$$

where $\Delta T_b$ = excess temperature associated with oil film

$\eta$ = microwave antenna efficiency

In principle, $T_{sky}$ can be measured by pointing the radiometer upward but models can also be used if certain environmental factors are measured or known (temperature profile, humidity profile, etc.).

The image then presents $\Delta T_b$ in two dimensions. Because the apparent temperature in the scene can be related to film thickness, a method has been developed to derive this information and is described in Section 3.1.2.

A number of workers have investigated the minimum film thickness that can be detected on a calm surface. Hollinger[17] suggests 50

microns while Edgerton[18] estimates that the minimum thickness lies between 100 and 300 microns.

The increased apparent temperature, $\Delta T_b$, is a function of polarization as well as film thickness. The theory suggests that $\Delta T_b$ will be larger for the horizontal polarizations signals than for vertical.[15] This is confirmed by laboratory experiments.[18]

3.1.2 Derivation of Film Thickness

The relationship between film thickness and apparent temperature can be derived,[14] if the physical properties of the oil and ocean are known. This requires information on the complex dielectric constant of the oil (at the particular microwave frequency of interest), and the temperature and dielectric constant of the ocean (which varies with salinity). Given this data, the film thickness can be derived but only for thickness smaller than $\frac{\lambda}{2}$ (where $\lambda$ is the microwave wavelength in the oil). For higher thicknesses, an ambiguity results from the sinusoidal nature of the $\Delta T_b$ versus thickness curve.

The ambiguity can be resolved by using different observational frequencies. Figure 1a illustrates the theoretically derived dependence of increased temperature in the scene as a function of film thickness, for frequencies of 31.0 and 69.8 Ghz. Figure 1b illustrates the relationship of the 31.0 and 69.8 Ghz data as it relates to film thickness. Using these two frequencies, thicknesses out to 2.3 mm can be obtained, as opposed to the limits of 0.65mm at 69.8

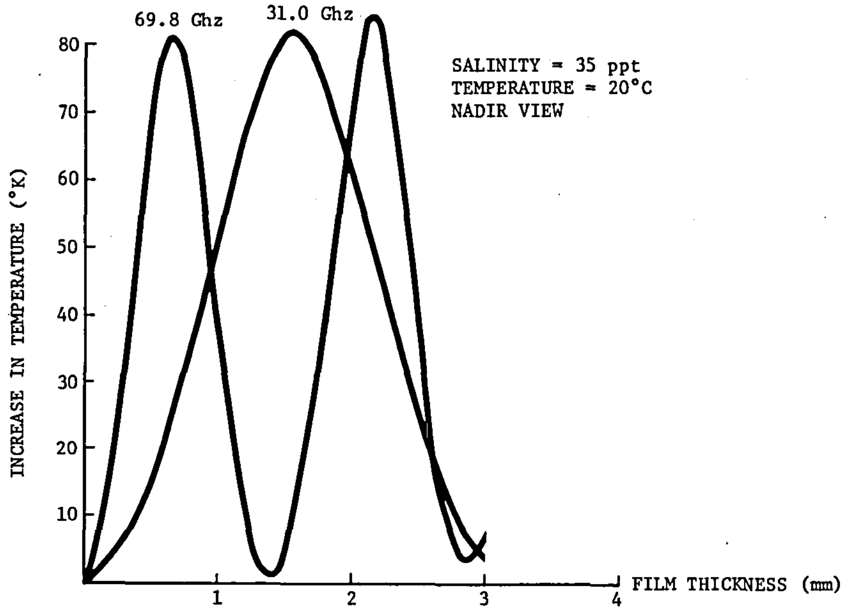


FIGURE 1a

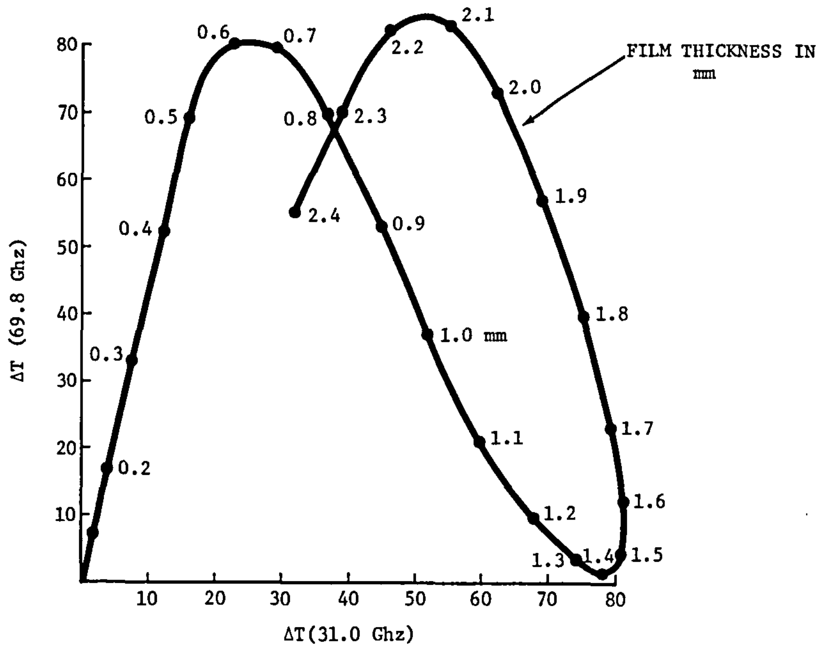


FIGURE 1b

**FIGURE 1**
**THEORETICAL DATA ON TEMPERATURE DEPENDENCE ON FILM THICKNESS (1a) AND FILM THICKNESS ON APPARENT INCREASED TEMPERATURE (1b). (AFTER 15)**

Ghz and 1.55 mm at 31.0 Ghz if only single frequency observations are used.

### 3.1.3 Conclusions

Edgerton[18] summarizes the performance of microwave radiometry for oil detection in an ideal environment as the following:

- signal strength increases with frequency
- films as thin as 100-300 microns can be detected. Since the principle limits to performance derive from detector noise, some improvement can be expected
- as expected from theory, horizontal polarizations produced the largest $\Delta T_b$
- viewing the surface from an angle near 45° provided the best performance (others tend to support this choice[19]) since it maximized the contrast between oil and water.

## 3.2 Performance in Rough Water

As indicated in the previous Section, the ability to measure the presence, areal extent and thickness of oil films has been confirmed by both theoretical and laboratory studies.[15,17,20] However, the ideal circumstances found in laboratory studies do not exist in experiments in the environment.

A number of changes can occur to the oil-water combination, primarily to the surface of the ocean. It is not uncommon to encounter a combination of waves and sea foam. The presence of waves raises the apparent emissivity of the unpolluted ocean surface, thereby increasing its apparent temperature. The increased emissivity is a function of the microwave frequency and is maximized for that part

of the spectrum with wavelengths comparable to the water wavelengths.[15] Foam also increases the effective emissivity of the ocean surface. The emissivity of foam can be as high as 0.8[2] while that of sea water is approximately 0.4.[2]

The effect of oil distributed onto a foam-covered, rough ocean surface (which appears warmer than its smooth counterpart) is to reduce the increased emissivity by damping the waves and foam. At the same time, the oil possesses a higher emissivity than the smooth ocean. As a result, conflicting processes occur in which the oil damps waves and reduces the apparent temperature while at the same time increasing the apparent temperature as a function of its thickness and naturally high emissivity. The water waves most affected by the presence of oil are those below 30 cm in wavelength. The shorter of these wavelengths may be completely eliminated with an efficiency which is independent of film thickness.[15] Hollinger illustrates[15] that the increased apparent temperature of the rough ocean is reduced as a function of microwave frequency, wind speed and roughness (a foam-covered sea being most impacted by the presence of oil).

An additional affect of a rough surface can be the creation of non-uniform oil film thickness (although this will also occur on smooth water for the very heaviest oils used in experiments).[17] The tangible impact of non-uniform film thickness is felt in efforts to estimate oil slick volume. If the film thickness varies on a

scale smaller than a resolution cell of the radiometer, estimates of film thickness over the slick will be in error and resulting efforts to compute oil volume will fail as well.

Efforts to make use of microwave radiometery to detect oil slicks in an ocean environment are documented in Section 4 of this report. Hollinger[15] indicates that, in a series of test spills over a one year period, both film thickness and volume can be adequately estimated, volume being estimated to within about 25 percent. Hollinger points out that each of the experiments was carried out under relatively low wind (and sea state) conditions. As a result, the opposing influences of the oil were not observed.

Other workers[18,21,22] have observed the effects of sea state reduction in the vicinity of the oil slick, as is evidenced by an apparent temperature which is smaller in the region of oil than in the clean water region.

The capability of microwave radiometry for remote sensing of oil slicks is conveniently summarized by utilizing the work of Edgerton et al.[18] After carrying out a series of tests on controlled and accidental oil spills in the ocean, their findings were that:

- films as thin as 10 to 20 microns could be detected for horizontal polarizations by the presence of an apparent temperature smaller than that of the surrounding ocean. That is, the performance was improved, through reduction in surface roughness, by a factor of about 10, relative to laboratory studies using a flat water surface and relying only on increased apparent temperatures resulting from the higher emissivity of oil
- vertically polarized signals are insensitive to changes in film thickness

- for thicker slicks (50 microns or more) horizontal signals exceeded vertical signals (as predicted by theory) and were positive relative to the clean ocean signal.

Edgerton suggests that for thin slicks, the increased temperature associated with higher emissivity is not sufficient to offset the reduction in sea state. Thinner slicks have a smaller increased temperature but nearly the same ability to damp the ocean waves contributing to the microwave emissions. The total effect is an apparent temperature smaller than that of the clean ocean.

Hollinger and Kenney[17] performed rough water tank tests for determining film thickness. They concluded that film thickness can best be measured in rough water by choosing as low an operating frequency as possible and using only a single frequency. Because the sinusoidal dependence of increased apparent temperature as a function of thickness can only be clearly seen in ideal, flat surface conditions, as illustrated in Figure 1a, the use of two frequencies for enhanced dynamic range in thickness measurements will not work. The use of a low single frequency allows measurement up to the first interference maximum. The lower the frequency, the larger the thickness which can be measured before any ambiguity is reached.

### 3.3 Application to Dissolved Pollutants

The majority of research on applications of microwave radiometry to remote sensing of pollution has been directed toward oil. Sandness et al.[2] point out that there is also a potential for microwave radiometry to be successful in sensing dissolved pollutants. In

contrast with the mechanisms for detection of oil, the presence of a dissolved pollutant can be expected to be detectable by its influence on the conductivity of the water. A strongly ionic compound will lower the emissivity of the water, thereby lowering its apparent temperature.

The application of microwave radiometry in the ocean is quite limited for this purpose, however, by the high natural conductivity of the ocean. Applications in fresh water seem much more likely.

A more complete discussion of detection, identification and quantification of pollutants other than oil by microwave remote sensing appears in Section 5.

## 4.0 LABORATORY DESIGN CRITERIA SUGGESTED BY FIELD EXPERIMENTS AND LABORATORY STUDIES

Experiments of both active and passive microwave remote sensing of oil spills have been carried out by a number of researchers, both in the laboratory and the field. Tables 4-I and 4-II illustrate many of the details associated with these experiments.

The experiments provide the opportunity to study the limitations of the techniques and thereby improve the usefulness of the proposed laboratory facility. Sections 4.5 and 4.6 relate the appropriate conclusions of the experiments and their significance for this report.

### 4.1 Conclusions from Radiometry Experiments in the Field

As expected from the theoretical analysis, the experimenters found[18,20] that even very thin oil slicks can be detected if the surface is agitated by waves. In fact, it is clear from the results that very thin slicks ( 10-20 microns) can be seen in rough water while it takes a slick of about 100 microns to be detectable on flat water.[18] The ability to observe the slightly higher apparent temperature resulting from the higher emissivity of oil, as can be done in the laboratory, was prevented in the case of very thin films (< 50 microns) by the noisy background in at least one case[21] so that suppression of waves by the oil slick proved to be the effective detection mechanism. This suggests that laboratory experiments should have a wave-making ability capable of simulating the conditions found in the ocean environment. Specifically, this would

TABLE 4-1 MICROWAVE REMOTE SENSING EXPERIMENTS (RADAR)

| GOAL | LOCATION | DATE | EXPERIMENTERS | METHOD | AMOUNT OF SPILL | OIL TYPE | SEA COND. | FREQ. | BEAM WIDTH | PLATFORM | NOTES | REF. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Map and measure extent of slick, test for best radar method, evaluation of flight path | Chedabucto Bay, Canada | Feb. 1970 | NRL | Wreck of tanker | 4.9 million liters | Bunker C crude | 0-2 meter swells | 0.428Ghz<br>1.228<br>4.458<br>8.910 | $12 \times 41^{\circ}$<br>$5.5 \times 12^{\circ}$<br>$5^{\circ}$<br>$2.5^{\circ}$ | Aircraft | 4 frequency dual polarized radar with scanning | 4;5,8,24, 30 |
| Determine volume and flow rate from multi-sensor observations | Mississippi Delta | March 1970 | TRW Systems and Remote Sensing, Inc. | Accidental spill | 5.4 million liters | Crude | - | 13.7Ghz | - | Aircraft | Also relied on IR imagery | 11 |
| At request of USCG participated with CG and LSU | Mississippi Delta | Mar. 16 1970 | NASA Marshall Space Flight Center | Drilling platform leak | 110 thousand liters per day | Crude | 0-1.3 meters | 13.3Ghz Scatterometer | - | Aircraft | Supported by ground truth and photographic observations | 24,31,32 |
| Support joint agency effort providing radar imagery. (See also radiometry experiment entry of same dates) | Pacific Ocean | Oct. 22-Dec. 3 1970 | NRL | Controlled spill | 830-2500 liters | No.2 Diesel<br>26.1 Gravity crude<br>21.6 Gravity crude<br>6175 fuel oil | Calm | 0.428Ghz<br>1.228<br>4.458<br>8.910 | $12 \times 41^{\circ}$<br>$5.5 \times 12^{\circ}$<br>$5^{\circ}$<br>$2.5^{\circ}$ | Aircraft | Vertical polarization synthetic aperture | 4,5,8 |
| Determine effectiveness of oil containment system. Use of microwave methods allowed determination of area and thickness of oil lost from containment system | Pacific Coast of California near Point Conception and Pt. Arguello | March 8 and 10 1972 | Hughes Aircraft | Controlled spill | 140,000 liters | Biodegradable soybean oil | Calm | X-Band | - | Aircraft | Viewed at $45^{\circ}$ from horizontal, side-looking radar | 9,33 |
| Establish repeatability of experiment of March 1972 | Santa Barbara Channel | Sept.25 1973 | Hughes Aircraft | Slicks produced by oil platform operations | Continuous | Crude | Calm | X-Band | $4^{\circ}$ | Aircraft | Synthetic aperture radar, $45^{\circ}$ off forward path and up to $60^{\circ}$ from horizontal | 9 |
| Compare performance of real and synthetic aperture radars | South and Central Coast of California | May 19-21 1976 | USCG<br>Univ. of Calif. Santa Barbara,<br>Motorola,<br>NRL | Natural oil seeps and oleyl alcohol spills | 10.0 to 15.4 sq. kilometers<br>small | Crude and oleyl alcohol | Calm | Radar | - | Aircraft | Airborne photography for ground truth | 34 |

TABLE 4-1 (Concluded)

MICROWAVE REMOTE SENSING EXPERIMENTS (RADIOMETRY)

| GOAL | LOCATION | DATE | EXPERI-MENTERS | METHOD | AMOUNT OF SPILL | OIL TYPE | SEA CONDITIONS | FREQ. | BEAM WIDTH | PLATFORM | NOTES | REF. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Detect oil spill and determine area of slick | Southern California Coast | August-September 1969 | Aerojet General Corp. | Controlled spill and accidental spill | 625-1325 liter<br>1325 liters<br>757 liters | Marine diesel,<br>20 API crude<br>30 API crude<br>42 API crude<br>Mixture of diesel fuel and 20 API crude, accidental spill | Calm<br>Calm<br>White caps<br>Calm<br>Calm | 13.4 Ghz<br>37 Ghz | $5^{o}$ | Aircraft | Viewed at $45^{o}$ | 18,23, 24,25 |
| Detect and discriminate oils | Gulf of Mexico near Alabama | April 1970 | Spectran, Inc. | Controlled spill | 0.2 to 0.4 liters per minute | No. 2 Fuel<br>No. 6 fuel,<br>9250 Lube Oil,<br>Gasoline<br>Light Crude,<br>Heavy Crude | - | 10.2 Ghz<br>30 Ghz | $4.6^{o}$<br>$2.4^{o}$ | Aircraft | Dual polarized radiometers looking $50^{o}$ aft | 19,24 25 |
| Confirm capability of remote sensing system on both smooth and rough seas | California | Oct. 22-Dec. 3, 1970 | Aerojet General, NASA-Ames Research Center, NRL, Univ. of Michigan | Controlled spill | 830-2500 liters | No. 2 Diesel,<br>26.1 Gravity Crude,<br>21.6 Gravity Crude,<br>6175 Fuel Oil | Calm | 37 Ghz<br>94 Ghz | $5^{o}$<br>$5^{o}$ | Aircraft | Forward looking by $45^{o}$. This entry describes Aerojet role | 26,27 |
| Test feasibility of detecting oil on the surface of the sea | California | Dec. 1970 Jan. 1971 | Spectran, Inc. | Controlled spill | - | No. 2 Fuel<br>No. 6 Fuel<br>Light Crude<br>Heavy Crude | Ranged from sea state 0 to sea state 3 | 10.2 & 30 Ghz | $4.6^{o}$<br>$2.4^{o}$ | Aircraft | Also included infrared and visible observations<br>Antennas viewed $50^{o}$ from nadir | 21 |
| Test passive multi-frequency microwave radiometry for detecting oil thickness | Wallops Island, VA (16 km off Chesapeake light tower) | August 1971 to August 1972 | NASA-Wallops, VIMS, USCG, Naval Research Laboratory | Controlled spill | 760 to 2380 liters | No. 2 Fuel<br>No. 4 Crude<br>No. 6 Crude | Calm<br>Swells $< 2m$<br>Wind $< 10m/s$ | 19.4 & 69.8 Ghz also 19.4 & 31.0 | $7.2^{o}$ | Aircraft | Included dye to reveal location of oil visibly | 15,20 28 |
| Detect oil slick, map volume from thickness and area. Identify oil type | Baltic Sea near Stockholm | Sept. 1974 | Swedish Coast Guard, Swedish Research Institute of National Defense Helsinki Univ. | Controlled spill | 1 $m^3$ | Crude | - | 3 bands near 4.75 Ghz | $3\text{-}4^{o}$ | Helicopter | - | 29 |
| Determine oil spill volume with passive microwave imagery. | - | Sept. 25 1975 | USCG NRL | Controlled spill | 760-2400 liters | No. 2 Fuel<br>No. 4 Crude<br>No. 6 Crude | Calm<br>Swells $\sim 1m$<br>Wind $\sim 10$ knot | 22 & 31 Ghz<br>90 Ghz | $64^{o}$ (full width scanner) | Aircraft | Used photography to record visible slick | 16 |

TABLE 4-II

LABORATORY STUDIES OF MICROWAVE REMOTE SENSING

| GOAL | LOCATION | DATE | EXPERIMENTERS | METHOD | MAXIMUM THICKNESS | OIL TYPE | TANK | FREQUENCY | BEAM WIDTH | NOTES | REF. |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Determine dependence of microwave emissions on oil thickness, type, temperature, observation wavelength, polarization, and viewing angle | - | April 1969 | Aerojet General | Graduated increase of oil thickness over simulated sea water | ≤1 mm<br>≤2 mm<br><1 mm | Bunker C<br>Gasoline<br>20 Gravity Crude<br>30 Gravity Crude<br>40 Gravity Crude | 4.9x1.8x0.5 meters | 13.4 & 37 Ghz radiometer | $5^{o}$ | Microwave rig transported by truck | 18 |
| Verify theoretical calculations of brightness temperature as a function of oil thickness and other parameters | - | Summer 1969 | Microwave Sensor Systems, Inc. Univ. of California Santa Barbara | Gradual increase in thickness (0.2 mm steps) | <5 mm | Mixture of Diesel Fuel and Motor Oil | 1.8 meters in diameter | 10.2 & 38.0 Ghz radiometer | - | Viewing angles ranged from $45^{o}$ to $55^{o}$ from nadir | 14 |
| Established 94 Ghz response to confirm results of earlier study at 37 and 13.4 Ghz | | 1970 | Aerojet General | Gradual increase of thickness in increments of 0.1 mm | <1 mm | No. 2 Diesel 26.1 API Crude | 4.9x1.8x 0.5 meters | 37 and 94 Ghz radiometer | $5^{o}$, $6^{o}$ | Measurements based on oil type, film thickness, temp. of oil-water, antenna polarization. Portable Laboratory. | 27 |
| Determine if thickness can be measured using multi-frequency method; measure dielectric constant | - | 1973 | NRL | Gradually increase thickness of film over distilled water | <0.1 mm<br><4 mm | No. 2 Fuel<br>No. 4 Crude<br>No. 6 Crude | 1.2 x 1.2 meters<br>Wood covered with foil | 19.4, 31.0 & 69.8 Ghz radiometer | - | Aluminum screen was used around tank to reduce effect of antenna pattern not intercepting tank. Horizontal polarization. $30^{o}$ viewing angle. | 15, 20, 35 |
| Develop methods for determining oil film thickness using multi-spectral microwave radiometry | Leonardo, N.J. | Nov. 17-21, 1975 | NRL | Oil dispensed from moving bridge over tank | ~6 mm | No. 2 Fuel | EPA Oil and Hazardous Materials Simulated Environmental Test Tank (OHMSETT) 20 x 200 x 2.5 Meters | 22.2 & 31.4 Ghz radiometer | $8.4^{o}$ @ 22.4 Ghz<br>$7.9^{o}$ @ 31.4 Ghz (0.5 m at water surface) | Tank includes wave-making devices | 17 |
| Study radar echo as function of oil film | Holland | 1975 | NIWARS* | Blow oil slick along tank with wind generator | - | Crude<br>No. 2 Motor<br>No. 30 Motor<br>Bunker | 100 m x 8 x x 0.5 m | 9.7 Ghz radar | $16^{o}$ transmitter<br>$7^{o}$ receiver | Used fresh water. Waves generated from airflow and hydraulic ram | 7 |

*Netherlands Interdepartmental Working Community for the Application of Remote Sensing Techniques

require the ability to create the high frequency, short wavelengths waves which are the predominant source of the higher emissivity of the rougher surface.

Among the other environmental factors which prevented easy detection of the oil by its higher apparent temperature was the foam produced by the oil-dispensing ship, since foam appears very warm with respect to the wavy ocean.

Experiments[16,28] also confirmed the ability of passive microwave systems to estimate oil spill volume by producing images of the spatial distribution of the slick and its thickness. Thus, it would be useful, particularly in attempting film thickness and spill volume tests in a tank, to allow the oil to spread to an equilibrium condition (unconfined by the tank walls). This suggests the need for either a large tank, which also provides that the antenna beam can be large, or the use of small spills, which require more control on beam size and orientation.

Some specific recommendations mentioned in reports describing the field tests include:

- study of low viscosity oils on sea water with multifrequency radiometry[18] as a function of film thickness, viewing angle and age of pollutant
- use viewing angle of 30 to 45°[18]
- use a receiver capable of detecting radiation with vertical and horizontal polarizations[21]
- operation near 35Ghz[21]

- employment of a receiver with a sensitivity of 0.1°K[21] with 1 second integration time.

## 4.2 Conclusions from Radar Field Experiments

Little can be extracted from the experiment descriptions which can be applied to the laboratory design, other than the information recorded in Table 4-I, such as operating frequency and beam width. In considering the choice of frequency made for the experiments summarized in the Table, it must be remembered that the equipment was usually designed to measure sea state rather than pollution. The instruments were simply adapted to the study of oil pollution and may not have used the optimum frequency. The observations were often made near 45° viewing angle.[5] Vertical polarization produced the highest contrast in the return signal.[5]

## 4.3 Conclusions from Laboratory Radiometry

Much of the laboratory work done on remote sensing by radiometry can be summarized as follows:[17,18,27]

- signals increase with increasing frequency but a gap in operating frequency exists from about 37 to about 94 Ghz due to atmospheric attenuation (as discussed later)
- the minimum detectable film thickness is 100 to 300 microns on flat water
- horizontal polarization provides the highest sensitivity
- best contrast can be achieved for viewing angles 30-45° from nadir
- virtually any material can be used to fabricate the tank
- the field-of-view of the receiver should be smaller than the tank dimensions

- although dual frequency observations can be used to measure film thickness, single, low frequency (2-8 Ghz) observations proved more effective in rough water and are able to measure thick films without ambiguity.

It is also important to recognize that the laboratory radiometry studies were carried out only at outdoor tank facilities. The following discussion describes why radiometric remote sensing cannot be carried out indoors. The radiation from the walls and ceiling of the building may be characterized by an effective temperature very close to that of the real temperature if the surfaces are rough and/or their emissivity is high. In effect, the ratio of $T_{sky}$ to $T_w$ (as depicted in Equation 4) becomes unity and the correction for reflection "sky" radiation cannot be carried out. Said another way, if $T_{sky} \simeq T_{water}$ then

$$\Delta T_a = (e + R)T_{sky} - e'T_{sky} - R'T_{sky}$$

Since both e + R and e' + R' equal 1,[14,15], $\Delta T_a$ is zero. No contrast can be achieved between the emitting film and the reflecting water. Hollinger of NRL confirmed this result in a private communication. Thus, any experiments on radiometry must be carried out at an outdoor tank facility.

4.4 <u>Conclusions from Laboratory Radar</u>

Relatively little work is reported in the literature on radar studies of oil spills carried out in the laboratory. In one case,[7] the author reports results which support the observations of field studies:

- because damping of waves creates the signal contrast, some surface roughness is required
- roughness of the water surface depolarizes the signal so that, for example, both horizontal and vertical components exist in the reflection of a horizontal transmission; the vertical to vertical polarization conversion produced the highest contrast
- a conventional water research tank was used
- shallow depths (as small as a few centimeters) are adequate as long as waves can be generated.

## 4.5 Conclusions-Radiometry

Recommendations for the development of a laboratory facility have been derived from the experiences reported in the literature. In selecting the criteria, the assumption is made that any experimental configuration should be readily adaptable to application in the environment.

### 4.5.1 Choice of Frequency

The selection of operating frequency is a trade-off between atmospheric attenuation effects (which are maximized between approximately 35 and 90 Ghz), spatial resolution (which improves with increased frequency for a given antenna size), receiver performance (which is best at low frequency) and signal (contrast between polluted and clean water) which is best at high frequency. The best compromise for performance, size, sensitivity, equipment availability, atmospheric transmission and reliability seems to be near 35 Ghz.[18,21,26,27] For dual-frequency thickness monitoring in

smooth water, the frequencies of 19.4 and 31 Ghz work well together.[28] For rougher water where thickness monitoring would be carried out at a single frequency, the range from 2 to 8 Ghz seems appropriate.[17]

Adequate performance can also be expected at 94 Ghz,[23,29] the next "window" in the microwave spectrum above 37 Ghz.

The limitation imposed by atmospheric transmissivity in the microwave region of the spectrum is due basically to the absorption by water vapor and oxygen.[36] The principal influence occurs from the 60 Ghz oxygen absorption band and the 22.2 Ghz band of water vapor. Figure 2 illustrates the attenuation (in db per kilometer) for a relatively low altitude (0.25 km) and humidity typical of that of Washington, D.C. Most laboratory and field studies utilize microwave frequencies associated with the transparency windows (10-20 Ghz, 30-40 Ghz and 70-100 Ghz).

### 4.5.2 Tank Size and Material

A number of different tank sizes and fabrication materials have been used successfully. This indicates that the designer has considerable freedom in choice of materials. In one case[15] a screen was placed around the tank to reduce emissions from the surface on which the tank was placed. Metal tanks are quite common and produce no special problems. Depth of water is also not a major issue since microwave propagation into water is quite poor.

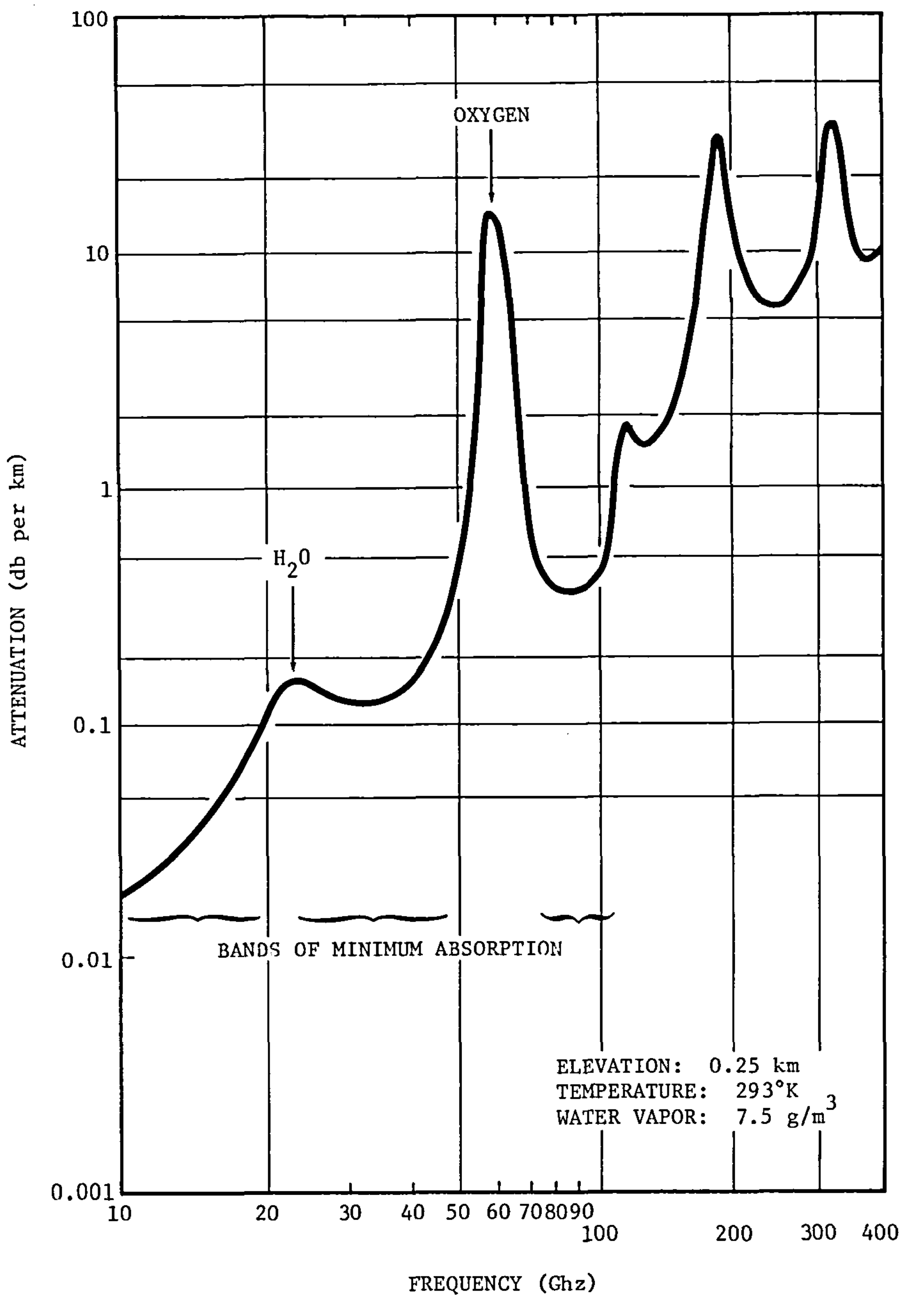


**FIGURE 2**
**ATTENUATION OF MICROWAVE FREQUENCIES BY THE ATMOSPHERE (AFTER 37)**

The only major restriction involves the placement of the tank in an environment where there are no warm overhead radiation sources. Also, the beam of the antenna should view only the water.

Tank size should be determined so that films can spread until only one mono-layer thick. Of course, a small tank can be used but requires a proportionately smaller receiver field-of-view.

#### 4.5.3 Wave Making

In view of the competing physical processes which can occur in applying radiometry to the remote detection of oil, it will be important to be able to generate waves in the tank during such experiments. The presence of short wavelength waves will also allow highly sensitive detection of very thin oil films in radar studies. Wave generation by conventional means (oscillating barrier) will not, by itself, be adequate. The addition of wind generated waves could provide the wide spectrum of wavelengths required.

#### 4.5.4 Handling of Materials

The materials which could be tested in the facility are mostly oil or oil-like (see Section 5 for a list of candidate pollutants). As a result, some safety issues must be considered.

Safe storage, handling and disposal of the pollutants is necessary. In addition, ventilation must be provided to areas not open to the atmosphere.

Tank cleaning will also be a problem, particularly with heavier oils, for which water-soluble solvents are less effective. Cleansing

of the tank walls will be important when experimenting with very thin oil films. Any residual material left on the walls may make its way onto the surface and affect the results. In at least one test tank,[17] bubblers near the walls are used to prevent the wall and oil from coming into contact.

Calibration methods for both thickness and volume of the film will be required if testing of thickness monitoring is to be carried out. Typically, thickness was estimated from the size of the oil film and knowledge of quantity of spilled oil.[15]

Film dispersion in layers of increasing thickness requires some method of metered flow. In one case,[17] oil was dispensed at a uniform rate from a moving bridge over the test tank. It was assumed that the oil formed a layer of uniform thickness. It was apparent from observation that a number of factors combined to create non-uniform thickness. These effects included wind-created waves, waves produced by the wave maker, residue on the surface of the water, etc.

Because the performance of the remote sensors is a function of the conductivity of the polluted water, consideration should also be given to methods for conveniently producing sea water salt concentrations.

4.5.5 Radiometer Performance

The typical recommendations for radiometer performance and viewing angle are [18,21]

| | |
|---|---|
| Temperature Resolution: | 0.1°K |
| Time Constant: | 1 second |

| | |
|---|---|
| View Angle: | 45° from horizontal |
| Polarization: | horizontal and vertical |

#### 4.5.6 Pollutants to be Studied

Section 5 provides a complete discussion of the pollutants (including oil and other materials) which might be studied using microwave radiometry.

### 4.6 Conclusions-Radar

The general conclusions reached in the discussion of development of a laboratory facility for radiometry apply in the case of radar.

The exceptions relate to two issues:

- the different set of pollutants which might be studied in the radiometry and radar cases (which are described in Section 5) and,
- the capability to perform indoor experiments with a radar test set-up.

## 5.0 CANDIDATES FOR POLLUTION STUDIES

Other Sections of this report make clear that both radar and passive microwave radiometry can be effectively used to measure features of oil pollution on the surface of the ocean. Clearly, it is also important to identify the possible application of these techniques to pollutants other that oil.

Although a literature search and conversations with experts have revealed no experiments attempting to utilize microwave techniques for pollutants other than oil, at least one document(2) does attempt to define those pollutants for which detection, identification and quantification can occur. The report describes a study which reviewed the chemical and physical properties of the 400 chemicals listed in the Coast Guard's Chemical Hazardous Response Information System (CHRIS). These properties were then compared with the detection capabilities of a number of remote sensing methods, including radar and microwave radiometry. In the remainder of this Section, the appropriate results of that study are summarized.

### 5.1 General Considerations

The first issue to be considered in assessing whether the sensing method can detect, identify, or quantify a particular pollutant is a determination of the "accessibility" of the pollutant. For example, a microwave system is incapable of detecting materials submerged deep in water, due to its poor propagation in that medium. Accessibility, then, is defined in this context, as the probability

that the radiation to be detected by the sensor can interact with the pollutant, taking into account the possible limitations imposed by environment.

Table 5-I summarizes the opinion of Sandness et al.(2) with regard to accessibility. For convenience, a ranking system was devised as a measure of the level of accessibility. It is clear from the Table that materials which float but are unsoluble in water are most detectable for both sensor methods while those which sink (neither soluble nor float) are not detectable. For convenience, accessibility groups (not necessarily related to rankings) have also been defined.

Second, classification was made of the types of material properties which coincide with the detection properties of the sensor systems. The result of that analysis appears in Table 5-II. As in the case of accessibility, a numerical scale was assigned as a measure of performance. The methods of remote sensing by microwaves are known to depend either on the conductivity of the material, if it is soluble (since this affects the reflectivity or emissivity of the polluted water) or on the mechanical properties of materials which are insoluble and float (since they form films which can, like oil, suppress waves and/or alter the emissivity of the surface). As a result, the scale of sensor performance is related, in increasing order, to the conductivity and mechanical properties of the pollution. The ability of the sensors to detect pollution also depends

TABLE 5-I

ACCESSIBILITY AS DEFINED BY SANDNESS (2)

| Accessibility Group | Does the Material Float? | Is Material Soluble? | Instrument Performance Radiometry | Radar |
|---|---|---|---|---|
| 1 | Yes | Yes | 2 | 1 |
| 2 | Yes | No | 2 | 1 |
| 3 | No | Yes | 1 | 1 |
| 4 | No | No | 0 | 0 |

2 - probably accessible
1 - possibly accessible or accessible under certain conditions
0 - probably not accessible

TABLE 5-II

REMOTE SENSOR PERFORMANCE (after 2)

| | Increasing Performance → 0 | 1 | 2 |
|---|---|---|---|
| Radar | non-conducting materials | strongly conducting compounds in fresh water | viscous hydrophobic compounds* |
| Passive Microwave | non-conducting materials | weak conductors in fresh water | viscous hydrophobic compounds,* strong conductors in fresh water |

* Note: It is clear but not mentioned by Sandness that the compounds must be lighter than water.

on the conductivity of the medium into or onto which the pollution is discharged. Fresh water is specifically noted as a requirement for adequate performance, since the conductivity of ocean water is naturally high and can only be slightly altered by the presence of conductive pollutants.

## 5.2 Detection

Determination of whether a sensor can detect the presence of a pollutant depends both on its ability to detect radiation which can interact with the pollution (accessibility) and on the sensor's sensitivity to the physical or chemical features of the pollution (as described in Table 5-II). In effect, each of the 400 pollutants was investigated for the position it should assume in Table 5-II and for its accessibility. The product of the two values was then taken to be a measure of detectability. Tables 5-III and 5-IV illustrate the results of the analysis for passive microwave and radar remote sensing, respectively. Two points should be made regarding the contents of the Tables. First, a number of the pollutants are characterized by a low boiling point so that their existence as a water pollutant will be very short. This is indicated as note "a." Second, Sandness[2] has identified those pollutants for which signal-to-noise or other considerations may prevent detection even though they are potentially detectable. This is indicated by note "b."

Of the 400 materials on the CHRIS list, 48 can be expected to be detected by passive microwave methods and 79 by radar. In addition

TABLE 5-III

DETECTABLE MATERIALS (PASSIVE MICROWAVE)(2)

| Chemical | Accessibility Group | Notes |
|---|---|---|
| ammonium hydroxide (<28% aqueous ammonia) | 1 | b |
| butadiene, inhibited | 2 | a |
| butane | 2 | a |
| butylene | 2 | a |
| epoxidized vegetable oil | 2 | |
| ethane | 2 | a |
| ethyl chloride | 2 | a |
| ethylene | 2 | a |
| ethyleneimine | 1 | b |
| hydrogen sulfide | 2 | a |
| isobutane | 2 | a |
| isobutylene | 2 | a |
| isopentane | 2 | a |
| isoprene | 2 | a |
| liquified natural gas | 2 | a |
| liquified petroleum gas | 2 | a |
| methane | 2 | a |
| methyl chloride | 2 | a |
| nonylphenol | 2 | |
| oil, edible (castor, cottonseed, fish, olive, peanut, soya bean, vegetable) | 2 | |
| oil, fuel (Nos. 5 and 6) | 2 | |
| oil, miscellaneous,( absorption[b] lubricating, mineral[b], motor, neatsfoot, resin[b], rosin[b], tall, transformer) | 2 | |
| petrolatum | 2 | |
| polybutene | 2 | |
| propane | 2 | a |
| propylene | 2 | a |
| tallow | 2 | |
| tetradecanol | 2 | a |
| tridecanol | 2 | |
| undecanol | 2 | a,b |
| vinyl chloride | 2 | a,b |
| waxes (carnauba, paraffin) | 2 | |

Notes
a - residence time limited by evaporation
b - probably not currently detectable

TABLE 5-IV

DETECTABLE MATERIALS (RADAR)[2]
(All Materials are in Accessibility Group 2)

| Chemical | Notes |
|---|---|
| butadiene, inhibited | a |
| butane | a |
| butylene | a |
| camphor oil | |
| decaldehyde | |
| diisobutylcarbinol | |
| diisobutylene | a |
| dioctyl adipate | |
| dioctyl phthalate | |
| epoxidized vegetable oils | |
| ethane | a |
| ethylene | a |
| 2-ethyl hexanol | |
| ethyl hexytallate | |
| glycidyl methacrylate | |
| heptanol | |
| hydrogen sulfide | a |
| isobutane | a |
| isobutylene | a |
| isodecyl alcohol | |
| isodecaldehyde | |
| isooctyl alcohol | |
| linear alcohols (12-15 carbons) | |
| liquified natural gas | a |
| liquified petroleum gas | a |
| methane | a |
| methyl chloride | a |
| mineral spirits | |
| naphtha (coal tar, solvent, Stoddard solvent, VM&P) | a |
| nonanol | |
| nonylphenol | |
| octanol | |
| oils (clarified, crude, diesel) | |
| oils, edible (castor, cottonseed, fish, olive, peanut, soyabean, vegetable) | |
| oil, fuel (No. 4, No. 5, No. 6) | |
| oil, miscellaneous (absorption, coal tar, lubricating, mineral, mineral seal, motor, neatsfoot, penetrating, resin, road, rosin, sperm, spindle, spray, tall, tanner's, transformer) | |

TABLE 5-IV (Concluded)

| | |
|---|---|
| petrolatum | |
| petroleum naphtha | a |
| polybutene | |
| propane | a |
| propylene | a |
| propylene butylene polymer | |
| propylene tetramer | |
| tallow | |
| tetradecanol | a |
| tridecanol | |
| undecanol | a |
| vinyl chloride | a |
| waxes (carnauba, paraffin) | |

Note
a - residence time limited by evaporation.

to the materials listed in the Tables, the sensing methods also exhibited the capability to detect a large number of other pollutants but with smaller probability of successful detection. For that reason, only the most likely candidates have been included in the Tables.

## 5.3 Identification

The identification of pollutants is assumed in Sandness' analysis[2] to be related to both detectability and to potential identification factors unique to each pollutant. The factors relate to the accessibility groups depicted in Table 5-I. The product of the detectability rankings and identification factors was then used to define identifiability. The analysis is of little use for microwave remote sensors, however, because their identification capability is so poor.

## 5.4 Quantification

Finally, Sandness determined the ability of each remote sensing method to quantify the amount of pollution, based on a two-part definition. The first definition involves the ability to determine the volume or thickness of a spill, particularly in the case of pollutants which remain on or near the water surface. A second definition applies in the case of the pollutants which are soluble in water. In this second case, the ability to determine concentration is the measure of capability of the technique. Quantification of a spill requires first that the pollution is detectable so the results

of Section 5.2 are used with detectability factors associated with each sensing technique and accessibility group. The quantifiability factor is defined as

2 = probably effective for quantification

1 = possibly effective

0 = probably ineffective.

Table 5-V illustrates the results of the analysis of instrument performance. Only passive microwave methods can be expected to make estimates of quantity of pollution and then only for materials which float and are insoluble. This result is derived from the fact that passive microwave remote sensing systems have demonstrated a capability to detect the areal extent of oil spills as well as make reasonably accurate estimates of film thickness so that volumetric estimates can be made. The film thickness measurements necessary for volume estimates cannot be carried out with radar sensing. Table 5-VI illustrates the result of combining the detectability data with the quantification which will result from the various sensor/material combinations.

The quantifiability scores depicted in Table 5-VI are much lower than the highest possible score. Sandness defines a score of 1 or 2 as "quantification possible under certain circumstances." This may be interpreted as indicating that under ideal conditions (as might be found in the laboratory) study of the quantifiability of the various pollutants would not be impossible.

TABLE 5-V

QUANTIFICATION FACTORS

| Accessibility Group | Passive Microwave | Radar |
|---|---|---|
| 1 | 0 | 0 |
| 2 | 1 | 0 |
| 3 | 0 | 0 |
| 4 | 0 | 0 |

0 - probably ineffective

1 - possibly effective

TABLE 5-VI

QUANTIFIABLE MATERIALS (PASSIVE MICROWAVE)
(All Materials are in Accessibility Group 2)

| Chemical | Quantifiability ( Maximum = 4 ) | Notes |
|---|---|---|
| adiponitrile | 1 | |
| benzaldehyde | 1 | |
| butadiene, inhibited | 2 | a |
| butane | 2 | a |
| butylene | 2 | a |
| camphor oil | 1 | |
| decaldehyde | 1 | |
| n-decyl alcohol | 1 | |
| diisobutylcarbinol | 1 | |
| dioctyl adipate | 1 | |
| dioctyl phthalate | 1 | |
| expoxidized vegetable oils | 2 | |
| ethane | 2 | a |
| ethyl chloride | 2 | a |
| ethylene | 2 | a |
| ethylenediamine tetracetic acid | 1 | |
| 2-ethyl hexanol | 1 | |
| ethyl hexyl tallate | 1 | |
| glycidyl methacrylate | 1 | |
| heptanol | 1 | |
| 1-heptene | 1 | a |
| hydrogen sulfide | 2 | a |
| isobutane | 2 | a |
| isobutylene | 2 | a |
| isodecyl alcohol | 1 | |
| isodecaldehyde | 1 | |
| isooctyl alcohol | 1 | |
| isopentane | 2 | a |
| isoprene | 2 | a |
| linear alcohols | 1 | |
| liquidifed natural gas | 2 | a |
| liquified petroleum gas | 2 | a |
| methane | 2 | a |
| methyl chloride | 2 | a |
| mineral spirits | 1 | |
| naphtha (coal tar, solvent, Stoddard solvent, VM&P) | 1 | a |
| nonanol | 1 | |

TABLE 5-VI (Concluded)

| | | |
|---|---|---|
| nonylphenol | 2 | |
| ocatnol | 1 | |
| oils (clarified, crude, diesel) | 1 | |
| oils, edible (castor, cottonseed, fish, olive, peanut, soya bean, vegetable) | 2 | |
| oil, fuel (No. 4) | 1 | |
| oil, fuel (No. 5 and No. 6) | 2 | |
| oil, miscellaneous (absorption lubricating, mineral, motor, neatsfoot, resin, rosin, tall, transformer) | 2 | |
| oil, miscellaneous (coal tar, mineral seal, penetrating, road, sperm, spindle, tanner's) | 1 | |
| pentane | 1 | a |
| 1-pentene | 1 | a |
| petrolatum | 2 | |
| petroleum naphtha | 1 | a |
| polybutene | 2 | |
| propane | 2 | a |
| propylene | 2 | a |
| propylene butylene polymer | 1 | |
| propylene tetramer | 1 | |
| tallow | 2 | |
| tetradecanol | 2 | a |
| tridecanol | 2 | |
| undecanol | 2 | a |
| vinyl chloride | 2 | a |
| waxes (carnauba, paraffin) | 2 | |

Note

a - residence time limited by evaporation.

Finally, Sandness concludes that the limit of performance of each remote sensing technique is as follows:

| | |
|---|---|
| Passive microwave: | 1000 ppm concentration of pollution in fresh water<br>1-100 micron thickness of oil film |
| Radar: | Film thickness greater than 1 micron. |

## 6.0 CURRENT ACTIVITY*

A review of the dates of the references and bibliography of this paper reveal that the major thrust of research occurred in the early 1970's. During that period, the basic capabilities and limitations of microwave remote sensing were established. Subsequent and current efforts have been directed toward applications.

Current activity centers on two relatively independent areas. First, the Coast Guard is continuing development of the second version of its Airborne Oil Surveillance System (AOSS). The first version included both active and passive microwave remote sensors, as well as other sensing systems. The new version, known as AOSS II, will include no passive microwave remote sensors. It will include a 200kw side-looking real aperture radar and is expected for installation on the AOSS aircraft in 1980. Apparently, the decision to drop the passive system resulted from two factors: the lack of a semi-real time data display capability, which is possible with radar, and doubts within the Coast Guard concerning the value of thickness measurements (which was considered as the really unique feature of the passive technique).

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*The information of this section was derived from reference 10 and private communications with the following individuals:

J. Hollinger, U.S. Naval Research Laboratory
Lt. R.E. Schmidt, U.S. Coast Guard
W. Croswell, NASA, Langley Research Center
R. Vollmers, U.S. Coast Guard

The other major activity relates to the NASA program. It includes detailed studies of materials, indoor and outdoor tank tests and at-sea tests. In the first case, samples of polluted sea water are studied by placing them in a small microwave cavity so that determination can be made of the change in dielectric constant as a function of pollution concentration.

Tank tests are carried out on both the effect of foam on emissivity and, in conjunction with the University of Kansas, the measurement of radar cross sections by scatterometry.

At-sea tests include the observation of the slicks in the wake of ships and barges. While the content of these slicks cannot be exactly determined, they do provide a regular and convenient supply of polluted sea water which can be used for performance tests. In addition, tests are to be carried out in conjunction with the controlled oil spills sponsored jointly by The Environmental Protection Agency (EPA) and American Petroleum Institute (API). These spills, which are occurring in both the Atlantic and Pacific Oceans in the fall of 1978 and spring of 1979, are primarily designed to test spill control and clean-up equipment. Interested researchers have been invited to participate as well. In the tests in the fall of 1978, NASA made use of the four channel synthetic aperture radar developed by the Environmental Research Institute of Michigan and the dual channel microwave radiometer originally developed by Hollinger of the Naval Research Laboratory.

In summary, then, the research programs of the early 1970's have resulted in an operational capability, as evidenced by AOSS. A small research effort continues to exist within government. Virtually no effort is going into tested pollutants other than oil for their potential detectability by microwave methods.

## 7.0 CONCLUSIONS

It is clear from the discussion in this report that the technology for remote sensing of aquatic pollution by microwave techniques is well established, at least for oil and related substances. Any effort to continue this work should therefore emphasize a capability to test these techniques for the other substances mentioned in Section 5. It is true as well that the materials listed in Section 5 do not form a complete list. Additional materials will no doubt emerge and will require continued studies as new pollutants enter the environment.

Table 7-I summarizes the capabilities which are associated with various research conditions, including location and sensing method.

First, it is clear that indoor research activities are limited to radar studies. For the purpose of evaluating radar capabilities for pollutants other than oils, such a laboratory design would be useful, assuming that the design issues discussed in Section 4 can be satisfactorily incorporated. Before undertaking to develop such a laboratory, it would be appropriate to investigate the existence of an indoor tank facility having the appropriate design features.

Research out of doors allows study of radiometry for remote sensing. Tests can be carried out at sea, using either controlled oil (or other pollution) spills, or pollution episodes. Accidental spills of large quantities of pollution are, of course, unpredictable so that the research program would be intermittent. A more

TABLE 7-I

MICROWAVE RESEARCH CONDITIONS

| | Research Area | | |
|---|---|---|---|
| | Indoor | Outdoor | |
| | | At Sea | Laboratory |
| Radar | Oil and other pollutants | Limited number of controlled oil spills. Regular observations are possible of minor slicks of unidentified floating waste (mostly associated with ship wake or waste) | Oil and other pollutants |
| Radiometry | Precluded by high radiation background | | Oil and other pollutants |

attractive possibility is the detection of oily wastes associated with ships passing along a predictable course or the tracking of acid or sludge waste barges. These sources of ocean pollution are almost always active along the East Coast of the U.S. and have provided suitable test conditions for NASA researchers, according to Croswell of Langley Research Center. A problem with the use of such spills is the lack of appropriate information on the chemical constituents of the pollution. Without the support of boats for ground truth observations, aircraft remote sensing can only serve to establish the microwave capability for detection, as compared with visual or photographic observations of the spill. Testing of this type also precludes studies of detectability for the pollutants, other than oil, mentioned in Section 5 and any other pollutants which become candidates for a research program.

It is also evident from conversations with Croswell and Vollmers of the Coast Guard that at-sea testing using controlled spills of pollutants has become more difficult as environment restrictions are imposed. An exception is noted in the case of biodegradable oils, but this clearly excludes a wide variety of important pollutants. Some work in this area is to be carried out in conjunction with controlled spills jointly sponsored by The Environmental Protection Agency (EPA) and The American Petroleum Institute (API). Tests are now being conducted both in the Atlantic and Pacific (near San Diego) for the primary purpose of evaluating spill control and clean-up

equipment. Additional tests are to be carried out in the spring of 1979. In each case, participation of experts in all forms of remote sensing has been solicited.

Laboratory studies in an outdoor tank environment provide significant advantages, particularly in ease of obtaining true measurements on pollution concentration, thickness, etc. In addition, environmental factors of significance (such as wave height spectrum) can be strictly controlled. A decision to carry out experiments in an outdoor laboratory offers the opportunity to conduct the studies at an already existing tank.[17] This would require the development of portable microwave equipment which could be eventually used in airborne experiments. The alternative, developing a new outdoor test facility, must be evaluated both in terms of convenience and cost relative to using an existing facility.

## REFERENCES


1. J. Estes and L. Senger, "The Multispectral Concept as Applied to Marine Oil Spills," Remote Sensing of Environment, 2 No. 3, Oct. 1972.

2. G. Sandness, J. Washburn and S. Ailes, "Study of Detection Identification and Quantification Techniques for Spills of Hazardous Chemicals," prepared by Battelle, Pacific Northwest Laboratories, Richland, Washington, for U.S. Coast Guard, October 1976, NTIS Number ADA 036216.

3. R. E. Matthews (editor), "Active Microwave Workshop Report," NASA Report Number SP-376, Washington, DC 1975.

4. R. Pilon and C. Purves, "Radar Imagery of Oil Slicks," IEEE Transactions on Aerospace and Electronic Systems, AES-9 No. 5, Sept. 1973.

5. N. Guinard, "The Remote Sensing of Oil Slicks" in The Proceedings of the Seventh International Symposium on Remote Sensing of Environment, University of Michigan, 1971.

6. J. Hollinger, "Remote Passive Microwave Sensing of the Ocean Surface," in The Proceedings of the Seventh International Symposium on Remote Sensing of Environment, University of Michigan, 1971.

7. J. Van Kuilenburg, "Radar Observations of Controlled Oil Spills" in The Proceedings of the Tenth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, 1975.

8. R. Pilon and C. Purves, "Radar Detection and Monitoring of Oil Slicks" in "Remote Sensing of Southern California Oil Pollution Experiment" (W. E. Lehr, editor), U.S. Coast Guard, July 1971, NTIS Number PB-203 194.

9. J. Kotlarski and H. Anderson, "Oil Slick Detection by X-Band Synthetic Aperture Radar" in The Proceedings of the Ninth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, 1974.

10. D. Meeks, J. Bommarito, R. Schwantje and A. Edgerton, "Transfer, Installation and Flight Testing of the Modified Airborne Oil Surveillance System (AOSSII) in a HC-130B Aircraft," Final Report prepared by Aerojet ElectroSystems for U.S. Coast Guard, August 1977, NTIS Number A052434.

11. J. Kennedy and E. Wermund, "Oil Spills, IR and Microwave," Photogrammetric Engineering, 37, No. 12 1971.

12. R. Moore (editor), "Microwave Remote Sensors" in Manual of Remote Sensing (R. G. Reeves, editor-in-chief), American Society of Photogrammetry, Falls Church, Virginia, 1975.

13. J. Stratton, Electromagnetic Theory, McGraw-Hill, 1941.

14. J. Auckland, W. Conway and N. Sanders, "Detection of Oil Slick Pollution on Water Surfaces with Microwave Radiometer Systems," in The Proceedings of the Sixth International Symposium on Remote Sensing of Environment, University of Michigan, 1969.

15. J. Hollinger, "The Determination of Oil Slick Thickness by Means of Multifrequency Passive Microwave Radiometry," interim report prepared by NRL for the U.S. Coast Guard, June 1973, NTIS Number AD 771376.

16. B. E. Troy and J. P. Hollinger, "The Measurement of Oil Spill Volume by a Passive Microwave Imager," NRL Memorandum Report 3515, Naval Research Laboratory, Washington, DC, May 1977.

17. J. P. Hollinger and J. E. Kenney, "Evaluation of a Passive Microwave Technique for the Measurement of Oil Film Thickness in a Test Tank Environment," NRL Memorandum Report 3308, Naval Research Laboratory, Washington, DC, April 1976, NTIS Number AD-A026 829.

18. A. Edgerton and D. Trexler, "Radiometric Detection of Oil Slicks," prepared by Aerojet General Corp., for U.S. Coast Guard January 1970, NTIS Number AD-702402.

19. J. Aukland and D. Trexler, "Oil Pollution Detection and Discrimination by Remote Sensing Techniques" prepared by Spectran, Inc. for U.S. Coast Guard, October 1970, NTIS Number AD 716349.

20. J. Hollinger and R. Mennella, "Measurements of the Distribution and Volume of Sea-Surface Oil Spills Using Multifrequency Microwave Radiometery," NRL Memorandum 7512, Naval Research Laboratory, Washington, DC, June 5, 1973, NTIS Number AD-762753.

21. J. Aukland, J. Sohn and L. Rasmussen, "Multisensor Detection and Tracking of Controlled Oil Spills" prepared by Spectran, Inc., for U.S. Coast Guard May 1971, NTIS Number AD-741953.

22. B. Au, J. Kenney, L. Martin and D. Ross, "Multi-Frequency Radiometric Measurements of Foam and A Mono-Molecular Slick" in The Proceedings of the Ninth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, 1974.

23. C. Wezernak and F. Polcyn, "Technological Assessment of Remote Sensing Systems for Water Pollution Control" prepared by Willow Run Laboratories, University of Michigan, for EPA, April 1971.

24. C. Catoe, "The Applicability of Remote Sensor Techniques for Oil Slick Detection," U.S. Coast Guard Project 714104/A/009, February 1971, NTIS Number AD-728422.

25. J. Auckland, D. Trexlar, F. Orthlieb, "Multisensor Oil Spill Detection" in The Proceedings of the Seventh International Symposium on Remote Sensing of Environment, University of Michigan, 1971.

26. A. Edgerton and P. Hinds, "Microwave Radiometric Observations of Controlled Oil Spills" in "Remote Sensing of Southern California Oil Pollution Experiment" (W. Lehr editor), U.S. Coast Guard, July 1971, NTIS Number PB-203 194.

27. D. Meeks, D. Williams, R. Wilcox, and A. Edgerton, "Microwave Radiometric Detection of Oil Slicks" prepared by Aerojet General Corp. for U.S. Coast Guard, Report No. 1335-2, March 1971, NTIS Number AD 728551.

28. J. P. Hollinger and R. A. Mennella, "Oil Spills: Measurements of their Distributions and Volumes by Multifrequency Microwave Radiometry," Science 181, July 1973, pp. 54-56.

29. K. Kaski and A. Laaperi, "Remote Sensing of Oil Slicks with Microwave Radiometer" prepared at The Radio Laboratory of Helsinki University of Technology, Report S 83, 1976, NTIS Number 76-31722.

30. N. Guinard and G. Purves, "The Remote Sensing of Oil Slicks by Radar," Letter Report No. 5270-19, U.S. Coast Guard Project 714104/A/004, June 1970, NTIS Number AD 709982.

31. C. Catoe, "Results of Overflight of Chevron Oil Spill in Gulf of Mexico," U.S. Coast Guard Project 714104/A/004, August 1970, NTIS Number AD 714681.

32. K. Krishen, "Detection of Oil Spills Using a 13.3Ghz Radar Scatterometer" in The Proceedings of the Eighth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, October 1972.

33. R. Thaman, J. Estes, R. Butler and J. Ryerson, "The Use of Airborne Imagery for the Estimation of Area and Thickness of Marine Oil Spills: An Operational Example" in The Proceedings of the Eighth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, 1972.

34. J. Estes and S. Kraus, "Summary Evaluation of the Offshore Target Detection Capabilities of APS-94D and COR Radar Systems" prepared by the Geography Remote Sensing Unit, University of California, Santa Barbara, for U.S. Coast Guard, Dec. 1976, Report No. CG-D-125-76.

35. J. P. Hollinger and R. A. Mennella, "Measurements of the Distribution and Volume of Sea-Surface Oil Spills Using Multifrequency Microwave Radiometry" presented at The Second Conference on Environmental Quality Sensors, sponsored by the U.S. Environmental Protection Agency, Las Vegas, Nevada, October 1973.

36. B. Bean, E. Dutton and B. Warner, "Weather Effects on Radar" in Radar Handbook (M. Skolnick, editor), McGraw-Hill, 1970.

37. N. Dieter, J. Castelli, D. Ushakoff, "Radio Astronomy" in Handbook of Geophysical and Space Environments (S. Valley, editor), McGraw-Hill 1965.

## BIBLIOGRAPHY


Anon, "A Slick Analysis of Oil Slicks," Microwaves, October 1973.

Anon, "Oil Spill Shows on Radar," Oceanology 6, No. 2, February 1971.

Arams, F., Infrared-to-Millimeter Wavelength Detectors, Artech House, Dedham, Massachusetts, 1973, p. 11.

Attema, E., "Remote Sensing of Oil Pollution at the Sea Surface - IV, Scatterometry of Oil Slicks in a Wavetank," Netherlands Interdepartmental Working Community for the Application of Remote Sensing Techniques, no date.

Bentz, A. P., "Oil-Spill Identification and Remote-Sensing," in Abstracts of Papers of the American Chemical Society, 176, Sept. 1978.

Cox, C. and W. Munk, "Statistics of the Sea Surface Derived from Sun Glitter," Journal of Marine Research 13, No. 2, 1954.

Davies, J. and R. Vose, "On the Damping of Capillary Waves by Surface Films," Proceeding of the Royal Society, 286 (A), p. 218, 1965.

Droppleman, J. and R. Mennella, "An Airborne Measurement of the Salinity Variations of the Mississippi River Outflow," Journal of Geophysical Research, 75 p. 5909, 1970.

Edgerton, A., J. Bommarito, R. Schwantje and D. Meeks, "Development of a Prototype Oil Surveillance System, Final Report," prepared by Aerojet-General Corp. for U.S. Coast Guard Report No. CG-D-90-75, 1975. NTIS Number ADA011275.

Edgerton, A., F. Ruskey, D. Williams, A. Stogryn, G. Poe, D. Meeks and O. Russell, "Microwave Emission Characteristics of Natural Materials and the Environment (A Summary of Six Years Research)," prepared by Aerojet Electro-Systems Co., for Office of Naval Research, 1971.

Edgerton, A. and D. Trexler, "Oceanographic Applications of Remote Sensing with Passive Microwave Techniques," in The Proceedings of the Sixth International Symposium on Remote Sensing of Environment, University of Michigan, 1969.

Edgerton, A. and G. Woolever, "Airborne Air Pollution Surveillance System," in The Proceedings of the Ninth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, 1974.

Garrett, W., "Damping of Capillary Waves at the Air-Sea Interface by Oceanic Surface-Active Materials," Journal of Marine Research 25, 1967.

Guinard, N. W., "The NRL Four-Frequency Radar System," in Report of NRL Progress, 1969, Naval Research Laboratory, Washington, DC.

Hollinger, J. P., "The Determination of Oil Slick Thickness by Means of Multifrequency Passive Microwave Radiometery." Final Report Prepared for the U.S. Coast Guard, NRL Memorandum Report 2953, June 30, 1974.

Hollinger, J., "Passive Microwave Sensing of Oil Slicks," in The Proceedings of the Ninth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, 1974.

Hollinger, J. P., J. E. Kenney and B. E. Troy, "A Versatile Millimeter-Wave Imaging System," in IEEE Transactions on Microwave Theory and Techniques, MTT-24, November, 1976.

Horvath, R., W. Morgan, R. Spelling, "Measurements Program for Oil Slick Characteristic," prepared by Willow Run Laboratories, University of Michigan, for the U.S. Coast Guard, February 1970.

Jones, D., R. Landers and A. Pressman, "Aerial Remote Sensing Applications in Support of Oil Spill Cleanup, Control and Prevention," presented at the International Symposium on Environmental Monitoring, Las Vegas, Nevada, 1976. Institute of Electrical and Electronics Engineers, New York.

Kondratyev, K., Y. Rabinovich, V. Melentyev, and E. Shulgina, "Remote Sensing of Oil on the Sea Surface," in The Proceedings of the Tenth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, 1975.

Krishen, K., "Detection of Oil Spills Using 13.3Ghz Radar Scatterometer," Journal of Geophysical Research 78, No. 12, April 1973.

Krishen, K., "Remote Sensing of Oceans Using Microwave Sensors," in Remote Sensing: Energy-Related Studies (T. Veziroglu, editor), Wiley, New York, 1975.

Lehr, W. (editor), "Remote Sensing of Southern California Oil Pollution Experiment," prepared in the Pollution Control Division of the U.S. Coast Guard, July 1971.

Long, W., Radar Reflectivity of Land and Sea, Lexington Books, Lexington, Massachusetts, 1975.

Matsui, M., and S. Tsutsumi, "Detection and Analysis for Water Surface Covered with Oil Film," in The Proceedings of the Tenth International Symposium on Remote Sensing of Environment, Environmental Research Institute of Michigan, 1975.

Pronk, A., "Remote Sensing of Oil Pollution at the Sea Surface - II, Damping of Water Waves by an Oil Layer as a Possible Indicator for SLAR Observations," Netherlands Interdepartmental Working Community for the Application of Remote Sensing Techniques Report Number 22, 1975.

Thomann, G., "Remote Measurement of Salinity: Repeated Measurements Over a Single Flight Line near the Mississippi Sound," NASA Earth Resources Laboratory Report No. 079, 1973.

van Kuilenburg, J., "Remote Sensing of Oil Pollution at the Sea Surface - I, Review of Remote Sensing Methods Emphasizing Radar," Netherlands Interdepartmental Working Community for the Application of Remote Sensing Techniques Report Number 27, 1975.

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